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Some myths and realities about dust explosions



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A B S T R A C T

The necessary conditions for a dust explosion to occur are well-expressed by the explosion pentagon: (i) fuel, (ii) oxidant, (iii) ignition source, (iv) mixing of the fuel and oxidant, and (v) confinement of the resulting mixture. While it might seem relatively straightforward to prevent or mitigate a dust explosion by simply removing one of the pentagon elements, the field of dust explosion risk reduction is more complex. Building upon previous work by the author and other dust explosion researchers, the theme of the current paper is that this complexity is partially rooted in several erroneous beliefs. These beliefs ignore the realities found with full consideration of appropriate scientific and engineering principles. Several such myths and their factual counterparts are presented with an illustrative example.

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1. Introduction

There is a problem, the nature of which is not well-understood, in communicating the results of dust explosion testing and research to stakeholders in industry, government and the public. In a recent article on dust explosions, the current author was quoted as follows: *When I hear about yet another dust explosion, I hang my head. When someone who has been in the industry for a certain number of years says that they didn't know sugar or flour or aluminum could explode because they'd never seen it happen before – that's just wrong* (Kenter, 2009). The answer to this problem is neither as trivial nor as obvious as it may seem.

This plenary paper is an attempt to at least partially address the imbalance that exists between the worlds of the dust explosion specialist and the non-specialist. It is based (with relevant excerpts) on an earlier presentation and paper (Amyotte, 2010) as well as a more extensive overview of the subject (Amyotte, 2013). The premise of the treatment here is that dust explosions continue to occur, in part, because of a belief in various myths that lack a foundation in appropriate elements of the natural, management and social sciences and

engineering principles associated with dust explosion hazard identification and risk reduction.

1.1. Explosion pentagon

In reality, the explosion pentagon (Fig. 1) provides ample information about dust causation – and, therefore, dust explosion prevention and mitigation. In short, when the requirements of the pentagon are satisfied, the risk of a dust explosion arises. These requirements include the familiar need for a fuel, an oxidant and an ignition source, augmented by mixing of the fuel and oxidant, as well as confinement of the resulting mixture. The first of these additional components illustrates a key difference between dust and gas explosions – a solid rather than a gaseous fuel. In a dust/air mixture, the dust particles are strongly influenced by gravity; an essential prerequisite for a dust explosion is therefore the formation of a dust/oxidant suspension. Once combustion of this mixture occurs, confinement (partial or complete) permits an overpressure to develop, thus enabling a fast-burning flame to transition to a dust explosion.

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Table 1 – Selected myths and realities of dust explosions with explosion pentagon element(s) indicated (Amyotte, 2013).

Myth	Reality
Dust does not explode [Fuel]	Many of the dusts handled in industry are combustible and therefore present an explosion hazard. To conclude that a given material is non-explosible requires incontrovertible evidence.
Dust explosions only happen in coal mines and grain elevators [Fuel]	Dust explosions occur in a wide range of industries and industrial applications involving numerous and varied products such as coal, grain, paper, foodstuffs, metals, rubber, pharmaceuticals, plastics, textiles, etc.
A lot of dust is needed to have an explosion [Fuel]	Combustible dust clouds can be generated from layers of dust deposited on surfaces in thicknesses on the scale of a mm or less.
Gas explosions are much worse than dust explosions [Fuel]	Both gas and dust explosions have the potential to cause loss of life, personal injury, property damage, business interruption, and environmental degradation. The likelihood of occurrence and severity of consequences for a given fuel/air explosion, as well as appropriate prevention and mitigation measures, are most effectively determined by a thorough assessment of the specific material hazards and process conditions.
It's up to the testing lab to specify which particle size to test [Fuel]	Selection of a dust sample for explosibility testing requires close collaboration between the test facility and plant personnel. A key selection consideration is the particle size distribution of the sample to be tested; the test facility alone cannot specify this material property.
Any amount of suppressant is better than none [Fuel/Ignition Source]	Effective suppression of a dust explosion requires that sufficient inert dust be admixed with the fuel dust. Amounts of suppressant less than that required for complete suppression can lead to higher explosion pressures than for the case of the fuel dust alone (i.e., no added suppressant).
Dusts only ignite with a high-energy ignition source [Ignition Source]	Energetic ignition sources on the order of several thousand Joules are routinely used in closed-vessel dust explosibility testing to overcome ignitability limitations imposed by the harsh test conditions. There is clear evidence that some dusts will ignite at spark energies less than 1 mJ under conditions of lower turbulence intensity.
Only dust clouds – not dust layers – will ignite [Ignition Source]	Dust layers pose a unique hazard that is different from that presented by dust clouds. Dust layers themselves do not explode. They can, however, ignite due to self-heating or hot surfaces and smolder or cause flaming combustion.
Oxygen removal must be complete to be effective [Oxidant]	For a given dust, there are volume percentages of oxygen (less than the typical 21 vol% in air) for which an explosion will not be possible. The highest of these concentrations is known as the limiting oxygen concentration or LOC.
Taking away the oxygen makes things safe [Oxidant]	While it is true that some alternatives are <i>safer</i> than others, nothing is <i>safe</i> . Further, an attempt to remove one hazard can in fact introduce another. For example, replacement of oxygen with nitrogen can eliminate a dust explosion hazard while at the same time introducing an asphyxiation hazard.
There's no problem if dust is not visible in the air [Mixing]	Absence of airborne dust in work areas does not indicate the absence of a dust explosion hazard. Explosible dust clouds are optically thick; thus dust explosions occur as primary events inside process units (i.e., where people are not normally present). Secondary explosions caused by initially layered dust in work areas can, however, cause significant loss.
Once airborne, a dust will quickly settle out of suspension [Mixing]	There are a number of factors that have an influence on the ease of dispersion of a dust and the tendency of the particulate matter to remain airborne once a dust cloud has been formed. These include particle size, shape and specific surface area, dust density and moisture content, and agglomeration processes both pre- and post-dispersion.
Mixing is mixing; there are no degrees [Mixing]	The role of variable turbulence in determining the state of <i>mixedness</i> of a dust cloud is a dominant concern in understanding dust explosion likelihood and severity.
Venting is the only/best solution to the dust explosion problem [Confinement]	Dust explosion prevention and mitigation are most effectively accomplished by a hierarchical consideration of the various measures available – ranging, in decreasing order of effectiveness, from inherently safer design, to engineered safety (passive and active), to procedural safety. Explosion relief venting is a passive engineered approach to explosion mitigation.
Total confinement is required to have an explosion [Confinement]	The degree of confinement that will enable pressure buildup need not be complete. Partial confinement can occur as a facility design feature or can result from the actual process of explosion relief venting.
Confinement means four walls, a roof and a floor [Confinement]	Congestion in a workplace as well as the presence of turbulence-generating obstacles can facilitate flame acceleration and subsequent overpressure development. It is also possible to create a degree of confinement unintentionally by means of temporary structures.
The vocabulary of dust explosions is difficult to understand [Pentagon]	Dust explosion terminology, as used to describe various parameters such as maximum explosion pressure and rate of pressure rise, has a direct analogy to that used for gas explosions. It is incumbent on the management of an industrial facility to ensure that its workforce is familiar with this terminology from a process safety perspective and to the extent needed for hazard awareness in relation to specific job functions.

Table 1 (Continued)	
Myth	Reality
Dust explosion parameters are fundamental material properties [Pentagon]	Dust explosion parameters such as the volume-normalized maximum rate of pressure rise, K_{St} , are strongly dependent on material characteristics such as particle size and experimental conditions such as turbulence intensity. Therefore, they are not intrinsic or fundamental material constants. Standardized equipment and test methodologies are available for determining these parameters; these must be followed to generate test data for use with the measures identified in dust explosion prevention and mitigation standards.
It makes sense to combine explosion parameters in a single index [Pentagon]	There is no single index appropriate for an assessment of the overall dust explosion risk posed by a given material. Such an assessment, as previously mentioned, requires consideration of specific material hazards and process conditions. Most Safety Data Sheets for combustible dusts are inadequate in terms of conveying these specific material hazards.
It won't happen to me [Pentagon]	Belief that a dust explosion will not happen in a given facility handling combustible powders is rooted in an inadequate safety culture. The end result of such a belief is inevitably the very thing it denies – a dust explosion.

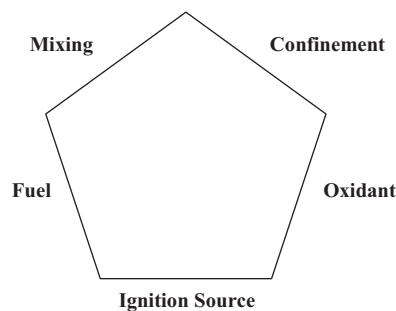


Fig. 1 – The explosion pentagon.

1.2. Myths and realities

A set of 20 dust explosion myths and realities has been developed as shown in Table 1. This compilation is largely personal, and is drawn from the current author's research activities and experience in providing dust explosibility test results to industry. Further details on all entries in Table 1 are given by Amyotte (2013).

2. Illustrative myth: Dust explosions only happen in coal mines and grain elevators

Here we examine the belief that dust explosions occur only – or primarily – in coal mines and grain elevators (i.e., the second myth in Table 1). Let us begin with a look back in history.

One of the first recorded accounts of a dust explosion was written in 1795 by Count Morozzo, who gave a detailed description of an explosion in a flour warehouse in Turin, Italy (Eckhoff, 2003). Although the explosion pentagon was not known as a causal framework at the time, it is interesting to note the pentagon elements in the following passage from the Count's report (Morozzo, 1795):

The boy, who was employed, in the lower chamber, in collecting flour to supply the bolter below, dug about the sides of the opening, in order to make the flour fall from the upper chamber into that in which he was; and, as he was digging, rather deeply, a sudden fall of a great quantity took place, followed by a thick cloud, which immediately caught fire, from the lamp hanging to the wall, and caused the violent explosion here treated of.

Fifty years later in 1845, Michael Faraday and a co-worker elucidated the key role of coal dust in the devastating explosion in the Haswell (U.K.) coal mine the previous year (Eckhoff, 2009). The significance of this finding lies in the fact that coal dust had now been shown to explode in the absence of firedamp (beyond the gas accumulation typically required for the initial ignition sequence). Prior to this observation, firedamp (methane) had been believed to be solely responsible for all such mine explosions.

To this day, dust explosions are often thought of as events that occur predominantly in underground coal mines and industrial grain processing facilities. This perception is accentuated by mine explosions throughout the world (especially, it seems, in China – whether they involve coal dust or not), as well as incidents such as the 1998 DeBruce grain elevator explosion in the United States (Kauffman, 2008).

2.1. Cyclical interest in an ever-present problem

Interest in the dust explosion problem is cyclical. At an international specialist meeting held in Montreal, Canada in 1981,



Fig. 2 – Polyethylene dust explosion – West Pharmaceutical Services, Kinston, NC (CSB, 2004).

Professor Bill Kauffman of the University of Michigan commented (Kauffman, 1982):

There seems to be little disagreement that the genesis for the revival of interest in agricultural dust explosions was the series of explosions which occurred during the Christmas Season of 1977 in four U.S. grain elevators.

It can similarly be argued that the current impetus for renewed concern about dust explosions (at least in North America) is a series of high-profile incidents that occurred in the United States over the previous decade and were the subject of investigation by the U.S. Chemical Safety Board (CSB). None of these incidents involved coal dust or grain dust, but rather polyethylene (Fig. 2; CSB, 2004), phenolic resin (Fig. 3; CSB, 2005a), aluminum (Fig. 4; CSB, 2005b), and sugar (Fig. 5; CSB, 2009). The most unfortunate and devastating aspect of these and other industrial dust explosions (CSB, 2006) is that they have all caused significant loss of life and injury.

Just as the dust explosion problem is not limited to coal or grain dust, neither is it limited to those materials involved in the incidents shown in Figs. 2–5.

2.2. Magnitude of the problem

Frank (2004) further illustrates the wide scope of the dust explosion problem by using incident data reported by the U.S. CSB and FM Global to show that dust explosions have occurred, for example, in the following industries with the indicated typical commodities: (i) wood and paper products (dusts from



Fig. 3 – Phenolic resin dust explosion – CTA Acoustics, Corbin, KY (CSB, 2005a).



Fig. 4 – Aluminum dust explosion – Hayes Lemmerz International, Huntington, IN (CSB, 2005b).

sawing, cutting, grinding, etc.), (ii) grain and foodstuffs (grain dust, flour), (iii) metal and metal products (metal dusts), (iv) power generation (pulverized coal, peat and wood), (v) rubber, (vi) chemical process industry (acetate flake, pharmaceuticals, dyes, pesticides), (vii) plastic/polymer production and processing, (viii) mining (coal, sulphide ores, sulphur), and (ix) textile manufacturing (linen flax, cotton, wool).

Dust explosion incident data are given for the United States in the previously referenced study on combustible dust hazards conducted by the CSB (CSB, 2006). The CSB researched the period 1980–2005 and identified 281 major combustible dust incidents resulting in 119 fatalities, 718 injuries and significant facility damage (CSB, 2006). Material categories used in the analysis were: (i) food, (ii) wood, (iii) metal, (iv) plastic, (v) coal, (vi) inorganic, and (vii) other (CSB, 2006). Industry classifications were: (i) food products, (ii) lumber and wood products, (iii) chemical manufacturing, (iv) primary metal industries, (v) rubber and plastic products, (vi) electric services, (vii) fabricated metal products, (viii) equipment manufacturing, (ix) furniture and fixtures, and (x) other (CSB, 2006).

Further illustrative case histories and statistical data for dust explosion occurrence can be found in a number of archival resources. Examples include Abbasi and Abbasi (2007), Amyotte and Eckhoff (2010), and Eckhoff (2003).

2.3. Reality

Dust explosions do not only occur in coal mines and grain elevators. They can arise in any scenario in which combustible



Fig. 5 – Sugar dust explosion – Imperial Sugar Company, Port Wentworth, GA (CSB, 2009).

dusts are stored, transported, processed or otherwise handled. It is not only coal dust and grain dust that should be of concern to managers, operators and other workers in an industrial facility handling bulk powders. Loss of life and injury, damage to facility assets, business interruption, and harm to the natural environment can result from dust explosions in a wide range of industrial applications.

3. Regulations, codes and standards

To combat the myths presented in Table 1, it is essential that researchers, test facility managers, and practitioners understand the need for adherence to government regulations as well as industry-consensus codes and standards. This means being knowledgeable about the organizations that develop such documents as well as the requirements for their effective implementation.

One of the first steps on the path to dust explosion risk reduction is identification of the nature of the combustible dust hazard itself. This typically involves explosion testing for parameters such as the maximum explosion pressure (P_{max}) and volume-normalized maximum rate of pressure rise (K_{St}). Standardized test methods must be employed for such purposes; the methods most familiar to the current author are those developed by ASTM International such as ASTM E1226-12a (ASTM, 2012). Testing standards for dust explosibility parameters also exist in other parts of the world (European, Asian and other international standards) (Amyotte, 2013).

Similarly, there are numerous codes and standards available for implementation of dust explosion prevention and mitigation measures including housekeeping, venting, automatic suppression, and the like. Examples include National Fire Protection Association (U.S.) documents such as NFPA 68 (NFPA, 2013a) and NFPA 654 (NFPA, 2013b), as well as European (EN) Standards and VDI Guidelines (Siwek and Cavallin, 2012).

In addition to standardized protocols for explosion testing, prevention and mitigation, it is of course necessary to follow all applicable regulations in matters such as hazardous area classification and selection of permissible equipment. These regulations are typically regional in nature, with the geographic extent of the region being a function largely of mutual agreements. The Health and Safety Executive or HSE (U.K.) web site (HSE, 2014) gives a good overview of two European Directives for controlling explosive atmospheres – ATEX 95 (ATEX Equipment Directive) and ATEX 137 (ATEX Workplace Directive).

This brief discussion of regulations, codes and standards is not intended to provide a comprehensive review of these issues on a global scale. Rather, the intent has been more modest: (i) to demonstrate that dust explosion hazard identification and risk reduction efforts must follow *standardized* procedures to be effective, and (ii) to indicate that the use of *non-standardized* procedures in these matters simply perpetuates the myths given in Table 1 (e.g., the myth that *dust explosion parameters are fundamental material properties*).

4. Dust explosion research needs

In reviewing the recent dust explosion literature for the book *An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace* (Amyotte, 2013), several new and existing research areas exhibiting knowledge gaps were identified. This section briefly addresses three of

these areas related to different fuel systems; the objective is to demonstrate how further research is needed to again combat the myths presented in Table 1. Other research topics are equally important and likewise merit concerted effort; one such example is the adoption and promotion of a quantitative risk-based approach to dealing with the dust explosion problem (see, for example, Abuswer et al., 2013a,b; Davis et al., 2011; Hassan et al., 2014, in press; Paltrinieri et al., 2013; van der Voort et al., 2007; Zhi et al., 2013).

4.1. Hybrid mixtures

Hybrid mixtures consist of a flammable gas and a combustible dust, each of which may be present in an amount less than its respective lower flammability limit (LFL)/minimum explosible concentration (MEC), and still give rise to an explosible mixture (Amyotte and Eckhoff, 2010). The concern with hybrid mixtures is often, though not always, focused on admixture of a flammable gas in concentrations below the LFL of the gas itself to an already explosible concentration of dust. Amyotte and Eckhoff (2010) note that the influence of the co-presence of a flammable gas on the explosibility parameters of a fuel dust alone is well-established. These effects include higher values of explosion overpressure and rate of pressure rise, and lower values of minimum explosible concentration and minimum ignition energy.

There remains, however, a need for continued research on hybrid mixtures (Worsfold et al., 2012). This is due in part to the range and diversity of industrial applications that can give rise to hybrid fuel systems as seen in recent studies (Amyotte et al., 2010; Dufaud et al., 2008, 2009; Garcia-Agreda et al., 2011; Glor, 2010; Perry et al., 2009; Pilao et al., 2006a,b; Sanchirico et al., 2011).

In this regard, Hossain et al. (2014) have noted the work of Garcia-Agreda et al. (2011) and Sanchirico et al. (2011). These authors employed an interesting graphical approach to represent four regimes of flammable gas/combustible dust mixtures dependent on whether the gas concentration is below or above the LFL, and whether the dust concentration is below or above the MEC. Amyotte (2013) referenced these studies (Garcia-Agreda et al., 2011; Sanchirico et al., 2011) in an attempt to refute the myth that *gas explosions are much worse than dust explosions* (Table 1).

4.2. Nano-size dusts

In addressing the myths *dusts ignite only with a high-energy ignition source, taking away the oxygen makes things safe, and once airborne, a dust will quickly settle out of suspension* (Table 1), Amyotte (2013) commented on an emerging area of dust explosion research involving nano-size powders. While nano-dust explosion research is indeed attracting increasing interest from industry, government and academia, there is at present a limited amount of experimental data in this field. Recent efforts in this regard include the studies conducted by Boilard et al. (2013), Bouillard et al. (2010), Dastidar et al. (2013), Holbrow (2009), Mittal (2014), Vignes et al. (2012), Wu et al. (2009), and Wu et al. (2010).

The results to date seem to indicate that explosion severity is not significantly different at the nano-scale than at the micron-scale; however, the likelihood of an explosion increases significantly as the particle size decreases into the nano-range (Amyotte, 2013). Agglomeration processes leading to rapid coagulation of particles in a dust cloud are thought to

be at least partially responsible for these phenomena (Eckhoff, 2012; Henry et al., 2013).

The field of nano-dust explosibility thus requires further investigation from fundamental, experimental and modeling perspectives. It seems we do not understand the impact on dust explosibility of particle size reduction into the nanometer range because we do not know whether explosions of these materials are actually occurring in clouds of primary nm-size particles, or whether such clouds can be generated in industrial processes (Amyotte, 2013).

4.3. Low K_{St} dusts

The myth *dust explosion parameters are fundamental material properties* (Table 1) arises in large part because of the empirical determination of the aforementioned volume-normalized maximum rate of pressure rise, or K_{St} . This parameter is used to design explosion relief vents and automatic suppression systems. Standardized K_{St} measurements (typically in 20-L and 1-m³ chambers) are especially important as industry turns to enhanced protection schemes such as flameless venting (Holbrow, 2013).

The use of energetic ignition sources in laboratory-scale (e.g., 20-L) test chambers has been shown to cause preconditioning of the combustion volume in terms of increases in fluid pressure and temperature as well as alteration to particle temperature and concentration prior to actual flame propagation (Cloney et al., 2013). Although overdriving has long been a recognized factor in dust explosion testing (Proust et al., 2007), explosibility parameters (e.g., K_{St}) determined using a 20-L chamber generally compare favorably with those measured in a 1-m³ chamber when both vessels are operated under standardized test conditions.

A notable exception is what have been termed *marginally explosible dusts*; these are materials with low K_{St} values of the order of 50 bar m/s as determined in a 20-L volume. The concern here is the occurrence of false positives whereby such dusts would not explode in the larger 1-m³ volume, their apparent explosibility at the scale of 20 L being due solely to overdriving. To complicate matters further, Bucher et al. (2012) provide empirical evidence that while not all low K_{St} (20-L) dusts explode in a 1-m³ chamber, some – especially metals – can actually yield higher values of explosion pressure and rate of pressure rise in the larger test volume.

As noted by Amyotte (2013), the issue of overdriving effects on marginally explosible dusts is important and needs to be resolved. There is a clear call from industry for cost-effective risk reduction measures appropriate for the actual degree of hazard. There are also clear incentives for test facility operators (20-L and/or 1-m³) as they strive to provide reliable, unambiguous data to their clients.

5. Concluding remarks

Twenty myths that play a key role in the occurrence of dust explosions have been identified. As previously mentioned, the listing presented here is drawn from the current author's experience; other researchers and practitioners would undoubtedly have their own examples to contribute. For example, one of the anonymous reviewers of this manuscript identified two additional myths that in his or her experience can have disastrous consequences: (i) a belief that safely operating below the minimum explosible concentration

of a dust is possible in a manner equivalent to operating below the lower flammability limit of a gas, and (ii) a belief that all dust explosions propagate by the same reaction mechanism, with no accounting for the possibilities of homogeneous combustion of released volatiles or heterogeneous combustion of solid particles.

Communication of the realities of dust explosions must therefore be an ever-present concern. In these communication efforts it is vital that we draw on the teachings afforded us by the natural, management and social sciences, as well as the fundamental principles of applied science. Adherence to relevant regulations, codes and standards, as well as targeted research efforts, are also needed on an ongoing basis.

Engineering is often about choosing the best solution from a number of good alternatives. There will thus always be a need for interpretation and opinion when it comes to engineering practice involving dust explosion prevention and mitigation. The choices made will be more amenable to implementation when they flow from a basis in fact (Amyotte, 2013).

References

- Abbasi, T., Abbasi, S.A., 2007. Dust explosions – cases, causes, consequences, and control. *Journal of Hazardous Materials* 140, 7–44.
- Abuswer, M., Amyotte, P., Khan, F., 2013a. A quantitative risk management framework for dust and hybrid mixture explosions. *Journal of Loss Prevention in the Process Industries* 26, 283–289.
- Abuswer, M.A., Amyotte, P.R., Khan, F.I., Morrison, L.S., 2013b. Quantitative risk management for dust and hybrid mixture explosions: framework and application. *Journal of Loss Prevention in the Process Industries* 26, 1530–1541.
- Amyotte, P.R., 2010. Dust explosions happen because we believe in unicorns. In: Keynote Lecture, Proceedings of 13th Annual Symposium, Mary Kay O'Connor Process Safety Center, Texas A&M University, College Station, TX, October 26–28, 2010, pp. 3–30.
- Amyotte, P., 2013. An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace. Elsevier/Butterworth-Heinemann, Waltham, MA.
- Amyotte, P.R., Eckhoff, R.K., 2010. Dust explosion causation, prevention and mitigation: an overview. *Journal of Chemical Health and Safety* 17, 15–28.
- Amyotte, P., Lindsay, M., Domaratzki, R., Marchand, N., Di Benedetto, A., Russo, P., 2010. Prevention and mitigation of dust and hybrid mixture explosions. *Process Safety Progress* 29, 17–21.
- ASTM, 2012. ASTM E1226-12a. Standard test method for explosibility of dust clouds, <http://www.astm.org/Standards/E1226.htm> (accessed 16.02.14).
- Boilard, S.P., Amyotte, P.R., Khan, F.I., Dastidar, A.G., Eckhoff, R.K., 2013. Explosibility of micron- and nano-size titanium powders. *Journal of Loss Prevention in the Process Industries* 26, 1646–1654.
- Bouillard, J., Vignes, A., Dufaud, O., Perrin, L., Thomas, D., 2010. Ignition and explosion risks of nanopowders. *Journal of Hazardous Materials* 181, 873–880.
- Bucher, J., Ibarreta, A., Marr, K., Myers, T., 2012. Testing of marginally explosible dusts: evaluation of overdriving and realistic ignition sources in process facilities. In: Proceedings of 15th Annual Symposium, Mary Kay O'Connor Process Safety Center, Texas A&M University, College Station, TX, October 23–25, 2012, pp. 688–697.
- Cloney, C.T., Ripley, R.C., Amyotte, P.R., Khan, F.I., 2013. Quantifying the effect of strong ignition sources on particle preconditioning and distribution in the 20-L chamber. *Journal of Loss Prevention in the Process Industries* 26, 1574–1582.

- CSB, 2004. Investigation report – dust explosion – West Pharmaceutical Services, Inc., Report No. 2003-07-I-NC. U.S. Chemical Safety and Hazard Investigation Board, Washington, DC.
- CSB, 2005a. Investigation report – combustible dust fire and explosions – CTA Acoustics, Inc., Report No. 2003-09-I-KY. U.S. Chemical Safety and Hazard Investigation Board, Washington, DC.
- CSB, 2005b. Investigation report – aluminum dust explosion – Hayes Lemmerz International-Huntington, Inc., Report No. 2004-01-I-IN. U.S. Chemical Safety and Hazard Investigation Board, Washington, DC.
- CSB, 2006. Investigation report – combustible dust hazard study, Report No. 2006-H-1. U.S. Chemical Safety and Hazard Investigation Board, Washington, DC.
- CSB, 2009. Investigation report – sugar dust explosion and fire – Imperial Sugar Company, Report No. 2008-05-I-GA. U.S. Chemical Safety and Hazard Investigation Board, Washington, DC.
- Dastidar, A., Amyotte, P., Turkevich, L., 2013. Explosibility of nano-sized metal powders, Paper No. 47b. In: Proceedings of 47th Annual Loss Prevention Symposium, 9th Global Congress on Process Safety, AIChE 2013 Spring National Meeting, San Antonio, TX, April 28 to May 1, 2013.
- Davis, S.G., Hinze, P.C., Hansen, O.R., van Wingerden, K., 2011. Does your facility have a dust problem: methods for evaluating dust explosion hazards. *Journal of Loss Prevention in the Process Industries* 24, 837–846.
- Dufaud, O., Perrin, L., Traoré, M., 2008. Dust/vapour explosions: hybrid behaviours? *Journal of Loss Prevention in the Process Industries* 21, 481–484.
- Dufaud, O., Perrin, L., Traoré, M., Chazelet, S., Thomas, D., 2009. Explosions of vapour/dust hybrid mixtures: a particular class. *Powder Technology* 109, 269–273.
- Eckhoff, R.K., 2003. Dust Explosions in the Process Industries, 3rd ed. Gulf Professional Publishing/Elsevier, Boston, MA.
- Eckhoff, R.K., 2009. Understanding dust explosions. The role of powder science and technology. *Journal of Loss Prevention in the Process Industries* 22, 105–116.
- Eckhoff, R.K., 2012. Does the dust explosion risk increase when moving from (m-particle powders to powders of nm-particles? *Journal of Loss Prevention in the Process Industries* 25, 448–459.
- Frank, W.L., 2004. Dust explosion prevention and the critical importance of housekeeping. *Process Safety Progress* 23, 175–184.
- Garcia-Agreda, A., Di Benedetto, A., Russo, P., Salzano, E., Sanchirico, R., 2011. Dust/gas mixtures explosion regimes. *Powder Technology* 205, 81–86.
- Glor, M., 2010. A synopsis of explosion hazards during the transfer of powders into flammable solvents and explosion prevention measures. *Pharmaceutical Engineering* 30 (1), 1–8.
- Hassan, J., Khan, F., Amyotte, P., Ferdous, R., 2014. Industry specific dust explosion likelihood assessment model with case studies. *Journal of Chemical Health and Safety* (in press).
- Hassan, J., Khan, F., Amyotte, P., Ferdous, R., 2014. A model to assess dust explosion occurrence probability. *Journal of Hazardous Materials* 268, 140–149.
- Henry, F., Bouillard, J., Marchal, P., Vignes, A., Dufaud, O., Perrin, L., 2013. Exploring a new method to study the agglomeration of powders: application to nanopowders. *Powder Technology* 250, 13–20.
- Holbrow, P., 2009. Explosion properties of nanopowders. In: Hazards XXI, IChemE Symposium Series No. 155, Manchester, UK, November 10–12, pp. 70–78.
- Holbrow, P., 2013. Dust explosion venting of small vessels and flameless venting. *Process Safety and Environment Protection* 91, 183–190.
- Hossain, Md.N., Amyotte, P., Abuswer, A., Dastidar, K., Khan, F., Eckhoff, F., Chunmiao, Y., 2014. Influence of liquid and vapourized solvents on explosibility of pharmaceutical excipient dusts. *Process Safety Progress* (in press).
- HSE, 2014. ATEX and explosive atmospheres, <http://www.hse.gov.uk/fireandexplosion/atex.htm> (accessed 16.02.14).
- Kauffman, C.W., 1982. Agricultural dust explosions in grain handling facilities. In: Lee, J.H.S., Guirao, C.M. (Eds.), *Fuel-Air Explosions*. University of Waterloo Press, Waterloo, ON, pp. 305–347.
- Kauffman, C.W., 2008. The DeBruce grain elevator explosion. In: Proceedings of 7th ISHPMIE, Volume III, St. Petersburg, Russia, July 7–11, pp. 3–26.
- Kenter, P., 2009. Big bang theory. *OHS Canada* 25, 42–47.
- Mittal, M., 2014. Explosion characteristics of micron- and nano-size magnesium powders. *Journal of Loss Prevention in the Process Industries* 27, 55–64.
- Morozzo, C., 1795. Account of a violent explosion which happened in the flour-warehouse, at Turin, December the 14th, 1785; to which are added some observations on spontaneous inflammations; From the Memoirs of the Academy of Sciences of Turin. The Repertory of Arts and Manufactures, London.
- NFPA, 2013a. NFPA 68: Standard on explosion protection by deflagration venting, <http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=68> (accessed 16.02.14).
- NFPA, 2013b. NFPA 654: Standard for the prevention of fire and dust explosions from the manufacturing, processing, and handling of combustible particulate solids, <http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=654> (accessed 16.02.14).
- Paltrinieri, N., Khan, F., Amyotte, P., Cozzani, V., 2013. Dynamic approach to risk management: application to the Hoeganaes metal dust accidents. *Process Safety and Environment Protection* (in press).
- Perry, A.J., Ozog, H., Murphy, M., Stickles, R.P., 2009. Conducting process hazard analyses for dust-handling operation. *Chemical Engineering Progress* 105 (2), 28–35.
- Pilao, R., Ramalho, E., Pinho, C., 2006a. Overall characterization of cork dust explosion. *Journal of Hazardous Materials* 133, 183–195.
- Pilao, R., Ramalho, E., Pinho, C., 2006b. Explosibility of cork dust in methane/air mixtures. *Journal of Loss Prevention in the Process Industries* 19, 17–23.
- Proust, Ch., Accorsi, A., Dupont, L., 2007. Measuring the violence of dust explosions with the 20 l sphere and with the standard ISO 1 m³ vessel. Systematic comparison and analysis of the discrepancies. *Journal of Loss Prevention in the Process Industries* 20, 599–606.
- Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A., Russo, P., 2011. Study of the severity of hybrid mixture explosions and comparison to pure dust-air and vapour-air explosions. *Journal of Loss Prevention in the Process Industries* 24, 648–655.
- Siwek, R., Cavallin, S., 2012. New revised European norm on dust explosion venting protection systems EN 14491. *Chemical Engineering and Technology* 26, 387–392.
- van der Voort, M.M., Klein, A.J.J., de Maaijer, M., van den Berg, A.C., van Deursen, J.R., Versloot, N.H.A., 2007. A quantitative risk assessment tool for the external safety of industrial plants with a dust explosion hazard. *Journal of Loss Prevention in the Process Industries* 20, 375–386.
- Vignes, A., Munoz, F., Bouillard, J., Dufaud, O., Perrin, L., Laurent, A., 2012. Risk assessment of the ignitability and explosivity of aluminum nanopowders. *Process Safety and Environment Protection* 90, 304–310.
- Worsfold, S.M., Amyotte, P.R., Khan, F.I., Dastidar, A.G., Eckhoff, R.K., 2012. Review of the explosibility of nontraditional dusts. *Industrial & Engineering Chemistry Research* 51, 7651–7655.
- Wu, H.-C., Chang, R.-C., Hsiao, H.-C., 2009. Research of minimum ignition energy for nano titanium powder and nano iron powder. *Journal of Loss Prevention in the Process Industries* 22, 21–24.

Wu, H.-C., Kuo, Y.-C., Wang, Y.-H., Wu, C.-W., Hsiao, H.-C., 2010. Study on safe transporting velocity of nanograde aluminum, iron and titanium. *Journal of Loss Prevention in the Process Industries* 23, 308–311.

Zhi, Y., Khakzad, N., Khan, F., Amyotte, P., Reniers, G., 2013. Risk-based design of safety measures to prevent and mitigate dust explosion hazards. *Industrial & Engineering Chemistry Research* 52, 18095–18108.